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Reuse of cold top ex-situ vitrified chromium contaminated soils in hot mix asphalt concrete

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ABSTRACT

REUSE OF COLD TOP EX-SITU VITRIFIED CHROMIUM CONTAMINATED SOILS IN HOT MIX ASPHALT CONCRETE

by
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This research investigated the pilot scale feasibility of the remediation of chromium contaminated soil through cold top ex-situ vitrification and the reuse of the vitrified products as highway construction aggregates. There are more than two million tons of chromite ore residues from the chromate extraction manufacturing leftover in Hudson County, New Jersey. They contained both un-leached hexavalent and un-oxidized trivalent chromium. Hexavalent chromium is well known as a group A human carcinogen. It is also considered an environmental and health hazard. Of the many ex-situ and in-situ physical, chemical, and biological treatment technologies for chromate production waste, the ability to reduce hexavalent chromium to trivalent chromium and at the same time inhibit the reversal back to hexavalent chromium as well as being able to demonstrate long-term, low toxic metal leaching characteristics is a critical criteria for technology evaluation.

Cold top ex-situ vitrification has been identified to satisfy the above criteria as a highly cost effective and environmentally sound physical treatment. The toxicity characteristic leaching process (TCLP) test results confirmed the effectiveness of the treatment technology. This research describes test results of the use of the vitrified material as aggregate in hot mix asphalt.

The physical properties of vitrified chromium contaminated soils were compared with the New Jersey Department of Transportation (NJDOT) specifications for aggregates to evaluate the reuse potential as a construction material. The crushed vitrified contaminated soils met all the desired NJDOT specifications for aggregates. The inclusion of those aggregates in hot mix asphalt concrete produced NJDOT acceptable mix. The freeze/thaw and wet/dry durability tests and permeability tests produced acceptable values for specimens made from both mixes at optimum asphalt contents. From the test results it can be concluded that the vitrified material can be used in the production of asphalt concrete providing less than 60% vitrified material is included in the mix.

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The author dedicates this thesis to his beloved mother.

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CHAPTER 1

INTRODUCTION

Chromium is a very important metal to humanity because of certain basic qualities that it possesses. Chromium is a very useful metal that is very prominent in industries like chemical, refractory, and metallurgical processes. The general public is more familiar with chromium as a shiny metal coating on other metals in many products, especially household appliances, cars, and motorcycles. In those instances the chromium coating has two important functions: esthetic, because it shines; protective, because it is not easily corroded, it protects the metal beneath from corrosion.

Chromium is found in nature as mineral chromite. It takes different forms both in its natural state and as modified by man. The most common and stable forms are trivalent and hexavalent chromium. In its hexavalent form, the US Environmental Protection Agency (EPA) classifies the metal as what is called Group A Human Carcinogen. There have been numerous researches and human evidences to support such a classification. In both of its prevalent forms, trivalent and hexavalent, chromium can cause allergic contact dermatitis.

There are two major differences between the trivalent and the hexavalent forms of chromium. Hexavalent chromium is water soluble, hence it is very mobile. Therefore, it has high potential for contamination of the environment, especially aquifers and surface water. On the other hand, the trivalent form of chromium generally exists as oxides

and/or is adsorbed on soil surface. It also precipitates as chromium hydroxide in any medium that is slightly acid or basic. These properties greatly reduce the potential for environmental contamination in comparison to hexavalent chromium.

Chromium played an important part in New Jersey's industry base from 1905 to 1971. During that period, chromate was being extracted from chromite ore. Three major facilities in Hudson County, New Jersey were involved in the extraction of chromium from mineral chromite. It is worth noting that the chromium industry in New Jersey stopped with emergence of environmental regulations (New Jersey Department of Environmental Protection and Energy, 1971).

Due to the absence of environmental regulations prior to 1971 the chromium industry neglected to properly dispose of the processing residue. Over 200 million tons of chromite ore processing residue are estimated to have been produced and left behind by the industry. That leftover material was used in the construction industry. It was spread as grading materials for roadways and as fill in other types of construction such as residential, industrial, and commercial.

NJDEP has classified over 150 sites in Hudson County as chromium contaminated areas. These sites have concentrations of chromium ranging from a few parts per million (PPM) to about 5 percent by weight. Some of the worst sites revealed 100 percent of Hexavalent chromium salt precipitation.

Vitrification is one of the technologies that have been explored for the treatment of the chromium contaminated soil. Meegoda et al., 1995 and 1996 reported on the assessment of vitrification as a viable treatment technology in relation to its effectiveness, reuse of end-product, volume reduction, and economics. The basic premises of the

previously mentioned research was as follows: during the vitrification processes, the more harmful form of chromium, the hexavalent, is reduced to trivalent chromium and is also incorporated in the glass matrix of the vitrified product. This allows the material to be delisted by the NJDEP as non-hazardous.

Meegoda et al, 1995 and 1996 used vitrified material from 9 different chromium contaminated sites in Hudson County. The vitrified material was successfully tested for its physical characteristics as potentially reusable as aggregate in asphalt, The physical properties were evaluated at the New Jersey Institute of Technology while the chemical tests were done at Stevens Institute of Technology.

This research assessed the physical characteristics of the vitrified material and its performance as aggregate in asphalt concrete. This bench scale experimentation follows up on the pilot scale technology demonstration for the vitrification of the soil from nine chromium contaminated sites in Hudson County as reported by Meegoda et al, 1995 and 1996. The chromium contaminated soils from Liberty Science Park (LSP) and Colony Diner (CD) were put through the ex-situ cold top vitrification process at Geotech Test Facility in Buffalo, NY. Chromium contaminated soils from these two sites were included in the pilot scale demonstration reported by Meegoda et al, 1995 and 1996. 150 pounds of the vitrified material were brought to the New Jersey Institute of Technology (NJIT) for evaluation as aggregate in asphalt using the New Jersey Department of Transportation (NJDOT) standards. The material was further incorporated into asphalt using the Marshall method and the properties of the asphalt mixes were evaluated and reported in this thesis.

of chromium contaminated soil. Chemical manufacturing in turn contributes mostly to chromium contamination in New Jersey. Coal and oil combustion generates about half of the airborne contaminated chromium [2].

The extraction process used dictates the type of contamination will result. Chemical manufacturing, chrome plating, textile manufacturing, and primary metal production produce the more toxic hexavalent form of chromium in the residue. Whereas, refinement of chromite ore, production of cement, ferrochromium, refractory manufacturing, MSW incineration, and steel production contribute to the less harmful trivalent chromium residues.

2.3 Chromium Production and Environmental Pollution

As found in nature, the original chromite ore $FeO.Cr_2O_3$ is stable, inert, and does not dissolve in either water or any acidic medium. However, during the manufacturing process, the chromite ore is combined with soda ash (Na_2CO_3) and lime (CaO) and heated at temperatures ranging from 1100°C to 1500°C. This process results in the formation of two chromate compounds that are soluble in water at 20°C to 30°C. Those two compounds are sodium chromate (Na_2CrO_4) and calcium chromate ($CaCrO_4$) with respective solubility of 5.2 mole/kg of water and 0.00071 mole/kg of water. The dissolving chromate found in the residue ranges from 0.7 to 5.0 percent by weight.

2.4 Chromium and Health Hazards

In its hexavalent form, chromium threatens human health. The Environmental Protection Agency (EPA) has classified chromium as a group A human carcinogen. The agency has

established the threshold limit value at 0.05 mg/m^3. If ingested in sufficient quantity, chromium causes acute gastrointestinal symptoms and bleeding, with potential for liver and kidney failure.

In most instances gastrointestinal (GI) absorption of ingested Cr(VI) compounds is greater than GI absorption of Cr(III) compounds, except for Cr(III) glucose tolerance factor. Human saliva and gastric juices reduce some hexavalent chromium to trivalent chromium, which crosses membranes with difficulty, with consequent poor gastrointestinal absorption. Once absorbed, there is nearly complete urinary excretion of chromium.

The kidney is the principal route of excretion of nearly all ingested chromium compounds. The form in which chromium is excreted has not been completely elucidated. Exposures of sufficient intensity to some chromium compounds produce kidney and liver damage, internal hemorrhage, dermatitis, and respiratory problems. Human lung tissue traps inhale trivalent chromium compounds in the form of small particles within the respirable range. With the exception of the lungs, tissue levels of chromium decline with age. The pharmacokinetics of chromium and its compounds depends upon oxidation state, solubility, and other physicochemical properties. More pharmacokinetic studies are needed to establish the precise role of these factors.

2.5 Nutritive Value of Chromium

Trivalent chromium is an essential element required for normal energy metabolism in human and other forms of life. Animal studies have shown that it is required for normal glucose metabolism because it acts as a cofactor for insulin via a mechanism which

remains to be elucidated. The toxicity of Cr(III) is quite low, either on an acute or chronic basis. The few chronic studies (mice and rats) that have been performed with Cr(III) have shown no adverse effects with high doses in either drinking water or the diet.

The National Academy of Sciences (NAS 1989) gives estimated safe and adequate daily dietary intakes (ESADDIs) of chromium of 20-80 g and 30-120 g for children of 1-3 and 4-6 years of age, respectively, and 50-200 g for children of 7-11+ years of age and adults. This range is based on the absence of chromium deficiency in the majority of the U.S. population whose average daily dietary consumption is 50 g. The upper limit of the range, 200 g/day is based on several human studies which showed that chronic dietary intake of Cr(III) at this level does not result in adverse effects. This daily intake figure was developed to be applied to short term and chronic exposures and was not meant to be applied to incidences involving single daily exposures.

2.6 Hexavalent vs. Trivalent Chromium

Chromium is a polyvalent metal that occurs most frequently as either Cr(III) or Cr (VI). We generally accept that only the commonly occurring oxidation states have biological importance. Chromium (II) is relatively unstable, being rapidly oxidized to Cr(III). It is unlikely that chromium (III) could be oxidized to chromium (VI) in vivo because the oxidation potential of Cr(III) to Cr(VI) is high. The Cr(VI) form, most frequently bound to oxygen, is a strong oxidizing agent. Human saliva and gastric juice will reduce some hexavalent chromium to trivalent chromium. Organic reducing matter in water readily reduces hexavalent chromium to the trivalent form.

2.7 EPA Classification of Chromium

The Environmental Protection Agency (EPA) established the maximum contaminant level (MCL) of total chromium in drinking water as 0.1 mg/l which was based on a maximum contaminant level goal (MCLG) of the same magnitude. The MCLG was developed from health effects information on Cr(VI) (EPA, 1991a). The EPA has also established a reference dose (RfD) for Cr(III) of 1mg/kgbw/day. The RfD was derived from a long term feeding study (Ivankovic and Preussman, 1975) in rats which used high doses (up to 5% of the diet) of chromium oxide. The study failed to detect adverse effects and, as a result, neither a no-observed-effect-level nor a lowest-observed-effect level was identified. The confidence in the RfD is low, particularly because the absorption of insoluble chromium salts is quite low (less than 1%) (IRIS, 1993). Although the EPA, in its guidelines for assessment of carcinogenic risk, may classify repeatedly inhaled Cr(VI) as a human carcinogen, there are inadequate data to conclude that chromium is carcinogenic via repeated ingestion. Accordingly, EPA deals with chromium as "not classified," a category for agents with inadequate animal evidence of carcinogenicity.

2.8 RCRA and HSWA

The intent of this study falls within the framework of the Resource Conservation and Recovery Act (RCRA) and its newer companion, the Hazardous and Solid Waste Amendment (HSWA). Subpart C of RCRA, titled the Hazardous Waste Program specifically regulates four heavy metals:

1. Chromium (Cr)
2. Lead (Pb)
3. Arsenic (As)
4. Mercury (Hg)

RCRA & HSWA have provisions for the reduction of the use of land disposal for management of hazardous waste. The solutions to the hazardous waste problem are those which destroy or detoxify the wastes. The proposed solution in this study not only provides for detoxification, but also the beneficial reuse of the detoxified product as a desirable and useful material.

Vitrification is the process of applying high temperature to soil with the addition of low cost materials such as sand or clay to form glass. The process can be adjusted to produce specific characteristics such as chemical durability and physical strength, the resulting product.

2.9 Chromium Contaminated Soil and Vitrification

Vitrification, or making glass out wastes, immobilizes the chromium in the glass matrix. It also destroys organic materials. The end product is a chemically durable, leach-resistant solid. Due to the melting and densification of minerals combustion or volatilization or organic, and vaporization of water the glass product from vitrification occupies less volume than the waste fed. Before reaching its melting point, which is higher than the vitrification temperature, chromium can be affected by the oxidation and reduction reaction. The innate impurities in the contaminated soils could lower the melting temperature in the range of 1513° to 1920°C [5].

Vitrification can treat a variety of mixed organic and inorganic contaminants in slag, soil, and sludge wastes. Organic materials are destroyed by pyrolysis and combustion [6]. Metals like chromium are incorporated in a leach-resistant glass matrix. When the silica content of the originally contaminated soil is high enough to form glass.

2.10 Advantage of Vitrification over Conventional Technologies

Section 121 (b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (May 22, 1995) mandates the US Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technology to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminant as a principal element: (U.S.EPA, 1992, EPE /540/s-92/009)

Containment barriers and solidification/stabilization using Portland cement or similar binders are the conventional technologies for remediation of metals contaminated sites. When correctly applied these technologies effectively reduce the mobility of metal contaminants [6]. However these immobilization technologies rank lowest in the hierarchy of waste management. None of the waste is recycled and the volume increases in most applications. Furthermore, long term durability of containment and solidification/stabilization has not been demonstrated. Vitrification on the other hand provides an alternative that reduces the volume of the waste and allows the reuse of the newly generated material.

The value of this research lies right in the mandate by CERCLA that favors technologies that recover resources to the maximum extent practicable and remedial actions in which treatment "permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances". Those preferences are reflected in this research by the following two factors: vitrification of the chromium contaminated soil which reduces its volume, toxicity and mobility and the subsequent incorporation in the asphalt matrix which provides an outlet for reuse of the material as demonstrated in the following chapter.

CHAPTER 3

EXPERIMENTAL PROGRAM

The chemical analysis of the chromium contaminated soil and the subsequently vitrified material was previously performed and reported by Meegoda et al, 1995 and 1996. That report concluded that the vitrified material passed all the NJDEP tests required for the possibility of reuse of previously hazardous waste as construction material. This new experiment included two steps: Firstly, the physical properties of the vitrified material from two sites (Colony Diner and Liberty State Park, Hudson County, NJ) were evaluated to determine their suitability for use as aggregate in asphalt pavement. Secondly, the vitrified material was incorporated into an asphalt mix using the Marshall method and the desired properties of durability, stability (strength), and permeability were evaluated.

3.1 Physical Characteristic Tests Performed on the Vitrified Aggregates

The physical tests performed included the following:

- Los Angeles Abrasion (ASTM C-131)
- Sieve Analysis (ASTM C-136 & C-117)
- Clay Lumps and Friable Particles (ASTM C 142-78)
- Sodium Sulfate Soundness (ASTM C 88-83)

* The tests are reported in the following sequence: purpose, apparatus, procedure, result, and discussion.

3.1.1 Los Angeles Abrasion (ASTM C-131)

3.1.1.1 Purpose of the Test: This test helps determine the potential resistance to degradation of a certain coarse aggregate due to impact and abrasion. It is extensively used to evaluate the fitness of aggregates from new sources for asphalt and concrete. The shape, the mineral composition, and the structure of the aggregate play very important roles in its fitness.

3.1.1.2 Apparatus for the Test :

Los Angeles Machine - The Los Angeles Machine is a steel drum, closed at both ends and having an inside diameter of 28 ± 0.2 in. (711 ± 5 mm). And an inside length of 20 ± 0.2 in. (508 ± 5 mm). The drum is mounted on stub shafts attached to the ends of the cylinder. The mounting is such that the drum may easily rotate with the axis in the horizontal position. An opening is provided in the drum for the introduction and retrieval of the test samples. A dust-tight cover is provided for the opening with means for bolting the cover in place.

Sieves - A regular set of sieves can be used for convenience, but the needed size is the No 12 (1.70 mm) sieve.

Balance - A balance or scale of an accuracy within 0.1% of the test load over the range of the test is used.

Charges - The charge consists of 12 steel spheres of about 46.8 mm in diameter. The individual weight of a sphere ranges between 390 and 445 g. The total weight of the charge is 5000 ± 25 g.

3.1.1.3 Test Procedure: The amount and gradation of aggregate is shown in tables 1 and 2. After proper drying and sampling, the aggregate and the charge of 5000 ± 25g are placed in the Los Angeles Machine. The drum is then rotated 100 times at a speed of 30 to 33 rpm. The aggregate is sieved to evaluate the percentage retained in the 1.70mm sieve. The total sample is returned to the Los Angeles Machine where it subjected to 400 more rotations. At this point, the aggregate retained in 1.70mm sieve is washed and then oven-dried at 105° C. the final weight is expressed as a percentage of the original weight.

The uniformity of the sample is also calculated and expressed as the ratio of the weight passing the 1.70mm sieve after 100 rotations to the weight passing the same sieve after the entire 500 rotations.

Table 1 Los Angeles Abrasion Test (Colony Diner)

Grading	Weight (g)	Retained after 100 Rotations		Retained after 500 Rotations		% Loss	Uniformity
		Weight (g)	%	Weight (g)	%		
C	5000	4526	91	3204	64.1	35.9	0.26
D	5000	4586	92	3464	69.3	30.7	0.27

Table 2 L.A. Abrasion Test (Liberty State Park)

Grading	Weight (g)	Retained after 100 Rotations		Retained after 500 Rotations		% Loss	Uniformity
		Weight (g)	%	Weight (g)	%		
C	5000	4430	88.6	3318	66.36	33.64	0.33
D	5000	4472	89.4	3447	68.94	31.06	0.34

3.1.1.4 Discussion of Results: The Los Angeles Abrasion test represents the worst conditions to which the average aggregate is expected to be subjected. All the samples tested clearly surpassed the 40 percent maximum weight loss required by NJDOT. It should be noted that the samples from Colony Diner were consistently more resistant to abrasion and impact after the first 100 rotations than those from Liberty State Park. The different results could have been fairly accurately predicted due to the structure, look, and feel of the aggregates. However, after the total of 500 rotations, the results tend to be very close for Grading D and there is even a reversal of roles for samples from the two sites for Grading C. The C D samples were generally more uniform than those from LSP. Overall, the different results for this test were satisfactory.

3.1.2 Sieve Analysis (ASTM C-136 & C-117)

3.1.2.1 Purpose of the Test: The sieve analysis is used to determine the grain size distribution for aggregates. In an asphalt mix design, the grain size distribution of the available aggregate sources is used to find a mix that would produce the best performing asphalt pavement and that also fit within the specifications of the USDOT. The accurate results of the grain size distribution plays an important role in the asphalt mix design and the subsequent performance of the asphalt pavement.

3.1.2.2 Apparatus for the Test:

Sieves - Different sizes are shown in tables 3 through 7. The sizes used depend on the specifications of the material being analyzed.

Balance - A balance or scale of an accuracy within 0.1% of the test load over the range of the test is used.

3.1.2.3 Test Procedure: The different sizes of sieves are mounted in an increasing size order in the sieve shaker starting with a pan at the bottom. The aggregate sample is subsequently placed in the top sieve, which is then covered. After securing the sieve shaker, it is activated for about 10 minutes during which the particles trickle down to the sieve size that is slightly smaller and is therefore able to retain them. The sample retained in each sieve is weighted. The result is expressed as the percentage passing each sieve size.

3.1.2.4 Results and Discussions: When plotted on the semi-logarithmic graph, which is customary for sieve analysis, the results took the shape of an S-curve. That is an indication that, even though the procedure used to crush the vitrified material and produce the aggregate was different than traditional methods, the end result was comparable: The resulting aggregate was densely graded with no major gap in between. Although the crusher was set with different opening sizes, the largest aggregate size passed the 1" sieve and was retained in the ¾" sieve. Therefore in this case, the maximum particle size was 1" because 100% of the crushed material went through it, and the maximum nominal size was ¾" because that was the first sieve that retained any of the aggregate. The results also showed that there was only a small percentage retained in the nominal size of ¾". There was also a consistently remarkable gap between the ¼" and

the 3/8" sieves. Tables 3 through 7 and figures 1 and 2 show the grain size distribution. Two different test results for the same aggregate were plotted on each graph.

3.1.3 Clay Lumps and Friable Particles (ASTM C 142-78)

3.1.3.1 Purpose of the Test: This test helps determine the suitability of the aggregate for use in asphalt. A high percentage of clay lumps and friable particles results in poor quality asphalt or concrete mixes. ASTM specifications C-33 must be referred to for the exact amount of clay lumps and particle friable acceptable in an aggregate sample.

3.1.3.2 Apparatus for the Test:

Balance - A balance or scale accurate to within 0.1% of the test sample.

Containers - The containers must be of a size that allows the spreading of the sample at the bottom of the container in a thin layer. The containers must be rust-resistant.

Sieves - As shown in tables 3 through 7.

Drying Oven - A forced-air oven capable of maintaining temperatures of 110 ± 5 °C.

3.1.3.3 Procedure: After the test samples were washed and oven-dried to a constant weight, they were spread in a thin layer on the bottom of different container. They were subsequently covered with distilled water and allowed to soak for 24 hours. The sample particles were then rolled and squeezed individually between the thumb and the forefinger in an attempt to break the particle into small sizes. The detritus was separated from the remainder of the sample by wet sieving. The sample was then oven-dried to a constant weight, allowed to cool, and weighed.

Table 8 Clay Lumps and Friable Particles (Colony Diner)

Type of Aggregate	Test Sample Weight (g)	Friable & Clay Lump (%)
Fine Aggregates	150	0.78
Coarse Aggregates	1200	0.06

Table 9 Clay Lumps and Friable Particles (Liberty State Park)

Type of Aggregates	Test Sample Weight (g)	Friable & Clay Lump (%)
Fine Aggregates	150	0.81
Coarse Aggregates	1200	0.07

3.1.3.4 Discussion of Results: The percentages of friable and clay lumps were very low. Such a low percentage 0could be expected from the average soil that has properly undergone vitrification. The samples from both sites easily met the NJDOT threshold for friable and clay lumps in aggregates which is set at 0.5 % for coarse aggregate and 5 % for fine aggregates.

3.1.4 Sodium Sulfate Soundness (ASTM C 88-83)

3.1.4.1 Purpose of the Test: This test simulates the effect that water will have on the aggregate upon freezing and thawing. It basically determines the soundness of the aggregate or its ability to withstand cycles of freezing and thawing without any major deterioration. This is done by alternate immersion of the aggregate in a saturated solution of sodium sulfate followed by oven-drying to dehydrate the salt that penetrated the permeable core spaces. When re-immersed in the sodium sulfate solution the expansive force of the crystals of sodium sulfate is comparable to the expansion of water upon freezing.

3.1.4.2 Apparatus for the Test:

Container - The container is used to immerse the samples. It should be perforated in a way that permits free access of the solution to the samples. It should also allow drainage without any loss of the aggregate. Wire mesh baskets with openings smaller than the smallest aggregate size are suitable.

Balance - A balance or scale accurate to within 0.1% of the test sample.

Drying-oven - A forced-air oven capable of maintaining temperatures of 110 ± 5 °C.

3.1.4.3 Preparation of Sodium Sulfate Solution: The solution is prepared by dissolving a USP grade salt in water at temperatures ranging between 77 to 86 degrees F. The mixture is then thoroughly stirred until the sodium sulfate is completely dissolved.

3.4.4.4 Procedure: The test samples were washed and oven-dried to a constant weight at 110 ± 5 °C. They were subsequently separated into different sizes by sieving and placed in the wire mesh container and then dipped in the sodium sulfate solution for 16 to 18 hours. The samples were submerged under at least ½ inch of the solution. After the desired period of time, the samples were then drained and placed in a over at a 110 ± 5 °C. They were regularly checked for constant weight at intervals of 2 to 4 hours. After constant weight is reached, the samples are allowed to cool at room temperature. The cycle was repeated 8 times in this test. The results are listed in tables10 and 11.

Table 10 Sodium Sulfate Test for Fine Aggregate (Colony Diner)

Sieve Size		Original Weight of Sample(g)	Percentage Loss (%)
Passing	Retained		
#4	#8	100	2.10
3/8	#4	150	1.80

Table 11 Sodium Sulfate Test for Coarse Aggregate (Liberty State Park)

Sieve Size		Original Weight of Sample(g)	Percentage Loss (%)
Passing	Retained		
¾"	3/8"	800	3.10

3.1.4.5 Discussion of Results: The sample and sieve sizes used depended on the availability of the vitrified material in any specific size. After the original crushing and subsequent sieve analysis of the aggregate, there was very little material larger than ¾"; Therefore The test for coarse aggregates was performed only on samples passing ¾" and retained in 3/8". The fine aggregate tested ranged between #8 to 3/8" with the #4 in between. Once again there was very little deterioration of the material indicating the ability of the vitrified soil to withstand possible freeze and thaw cycles.

3.2 Incorporation of the Vitrified Aggregate in the Asphalt Mix

The remaining sections of this chapter will focuss on the procedures used and the results from the incorporation of the vitrified aggregate in the Hot Mix Asphalt (HMA). Since the vitrified materials from both the CD and LSP sites met all the physical properties required by NJDOT for possible use in Hot Mix Asphalt pavement, the vitrified material was incorporated in an asphalt mix and the required laboratory performances were

investigated. The Marshall Method and the required tests that accompany this method to measure the performance of a mix and determine the optimum asphalt content for the mix were used.

3.2.1 Asphalt Mix Design Theories

A paving mixture is a combination of asphalt cement and aggregate blended together in precise proportions. The relative proportions and characteristics of these materials, and the air voids of the compacted mix, determine the properties of the mix. The performance of the mix in the field will depend on these properties. There are three methods used for the design of asphalt pavement in the United States: the Marshall Method, the Hveem Method, and the Superpave Method. The Marshall Method and the Hveem Method were both developed in the early 1940's in the United States. The Marshall Method was developed in the East, and the Hveem Method was refined in the West. While the Hveem Method is still widely used on the West Coast, the Marshall Method is the most widely used method in the eastern part of the country. The Superpave Method is fairly new. While there is tremendous data supporting the use of the Marshall Method and the Hveem Method, there is hardly any long term data for the Superpave Method. It is different from both of the previously mentioned methods in that it takes certain additional qualities and properties into consideration.

3.2.2 The Superpave Method: Since the 1940's not much research had been done in asphalt. In 1987, the federal government decided to invest in research, and a new method came about: the Superpave Method. The Superpave Mix Design Method was developed

by the federally funded SHRP (Strategic Highway Research Program). The thrust behind the Superpave system was to develop a performance-based design method that could reliably predict the performance of the paving mixture. The Superpave mix design is an attempt at a more rational method for determining asphalt mix material proportion. Compared to the Marshall method, Superpave establishes minimum mix design requirements for various environmental and loading conditions.

Regardless of the material, a mix design must meet or exceed minimum requirements. This establishes a standardized, performance based specification for asphalt mix design. A drawback is that there is little field performance data because specifications were developed using accumulative knowledge of the nation's top asphalt mix design and pavement engineering experts. Currently, numerous Superpave projects are being rigorously evaluated to verify the performance based specification. Once ready, the specifications can be optimized for field use.

3.2.3 The Marshall Method

This research utilized the Marshall Method because the contaminated sites in question are located in Hudson County, New Jersey. The Marshall Method is used by the New Jersey Department of Transportation. Even though there is a possibility that many federally funded highways will use the Superpave Method in the future, as of now almost most paving jobs in New Jersey are using the Marshall Method.

The Method was developed by Bruce Marshall, a Bituminous Engineer with the Mississippi Department of Highways. The US Army Corps of Engineers investigated the method in 1943 and decided to adapt the Marshall Method for use in mix design. Its

main purpose is for proportioning asphalt mix designs. With this approach, specific mix properties could be measured in a laboratory and correlated to performance in the field. Adaptability is the primary reason why the Marshall mix design is the preferred method for asphalt plant process control and final mix design acceptance. However, due to its empirical nature, there are no universal Marshall mix design performance criteria. This is due, in large part, to the fact that each transportation agency has different materials and environmental conditions with which to work; therefore, performance criteria for each agency will be different.

All three methods use basically the same aggregate and the same testing for aggregate. All the information and data used in this research will be valuable for use in any of these methods, even though this research will only use the Marshall Method.

3.2.4 Composition of Asphalt Pavement

Asphalt pavement is a general term applied to any pavement that has a surface constructed with asphalt. It is usually made out of three layers, or courses: the subbase, the base, and the surface course. The subbase is the very bottom course of the asphalt pavement, therefore, if the subgrade soil is of adequate quality and firmly compacted, it can serve as the subbase for the asphalt pavement. Otherwise, the subbase can be made of the following materials: asphalt base consisting of asphalt aggregate mixtures, crushed stone, slag, or gravel. Under certain circumstances, for example if there is an existing Portland cement concrete base of pavement, it can be used as the subbase.

The base is the layer of material immediately beneath the surface or intermediate course. It may be composed of crushed stone, crushed slag, crushed or uncrushed gravel,

and sand, or a combination of these materials. It may also be found with asphalt. It should be mentioned that both of the bottom courses because they play a structural role in the asphalt pavement, similar to the purpose of foundation in a building, are usually made of large aggregate (one inch or larger).

The surface course is made of well-graded aggregate and asphalt cement. The well-graded aggregate nominal size (meaning the smallest sieve size through which 100% of the material passes through) is usually less than 1½ inch in diameter. The aggregates make up to 96% of the asphalt pavement. The asphalt cement content of the mix usually varies from 3.5% to 6.0%.

In this research, asphalt cement percentages varying from 3.5% to 6.0% with an increment of 0.5% were used in order to determine the best asphalt percentages for our use. The 5.5% asphalt cement content was determined to be the best for our mix design because it gave excellent results in terms of voids in the asphalt mix, flow, and stability (strength). Several other samples were subsequently made in order to test the expected qualities of asphalt pavement such as durability permeability, durability (freeze/thaw and wet/dry cycles).

3.2.5 Experimental Mix Design Procedure

All asphalt mixes are designed for particular qualities. These qualities include stability, durability, workability and skid resistance. The mix design method and design requirements used in this experiment were per USDOT/FHWA. The mix design was prepared by proportioning the vitrified aggregate using the previously performed sieve analysis (tables 3 to 7 or figures 1 and 2). Since the maximum size of the aggregate

samples from both sites was one inch, an original mix using USDOT I-3 specifications was designed for each aggregate. The mix designs are shown in figures 3 and 4. The right mix design would provide an asphalt mix that has all the desired qualities in terms of stability, flow, voids in mineral aggregate (VMA), and air voids used to evaluate any design done by the Marshall Method.

3.2.6 Optimum Asphalt Content Determination

The optimum asphalt content is the percentage of asphalt cement at which a specific asphalt mix performs best in terms of the Marshall properties of stability, flow, and air voids. The range for the optimum asphalt content is usually between 3.5 and 6.0%. For each aggregate in this research, 3 asphalt samples were prepared for each asphalt content between 3.5 and 5.5% with an increment of 0.5%. A total of 15 samples were prepared and the different parameters evaluated for each aggregate. The results are plotted in figures 6 through 15.

3.2.7 Preparation of Asphalt Samples

Specified amounts of asphalt cement (ranging from 3.5 to 6.0%) based on the asphalt content needed was raised to a 325° F and was added to the aggregate mixture that was also at the same temperature. The aggregate mixture and the asphalt cement were thoroughly mixed as quickly as possible. Then the new asphalt mixture was spaded into a cylindrical mold (4" in diameter by 2.5" in height). A filter paper was placed at the bottom of the mold to prevent the mixture from sticking to the base plate. After spading and rodding the asphalt mixture 25 times with a metallic spatula, another paper filter was

placed on the asphalt mixture. The mold, the spatula, collar, and everything else that got in contact with the mix were also pre-heated at 325° F. The mold along with its base plate and collar were then placed on a pedestal where compaction took place.

The Samples were compacted with the Marshall hammer. 75 blows were delivered to each side of the samples emulating the roller pattern in the field. After compaction the specimens were allowed to cool and then extruded from the mold and tested for stability, flow, specific gravity, voids in mineral aggregates (VMA), Unit weight, and air voids.

3.2.8 Marshall Stability Results

The Marshall stability values represent the maximum amount of loading the pavement could take without being deformed permanently or failing. The resulting values for the first series of tests are plotted in figures 6 and 11. Asphalt contents ranging from 3.5 to 5.5% are plotted versus their respective stability values. For the Colony Diner samples, the graph clearly shows a steady increase in the stability values. At 5.5% asphalt content, the highest stability was reached. Since the stability was expected to culminate at 5.0% asphalt content and because the vitrified material was at a premium, no samples were prepared with 6.0% asphalt content. That highest stability value exceeded the USDOT criteria for light and medium traffic which are respectively 750 and 1200 lb. However, the 1800lb value required for heavy traffic was not achieved. The goal was to surpass the 1800lb necessary for heavy traffic.

The original stability values for the Liberty State Park samples were even lower than those of Colony Diner. The highest stability value was below the minimum

requirement medium traffic. The lower stability values were expected for the LSP samples since the aggregates constantly did not perform as well as the CD samples in all the aggregate physical tests. Furthermore, the polished surface and the sharp edges accentuated the advantage the CD samples would have over the LSP aggregates. The assumption in this case is that the asphalt cement would not adhere as well on that type of aggregate. Additionally, the mechanical integrity coming from the friction among the aggregates would be lessened because of the polished surface of the vitrified material from LSP. The aggregate form CD was much rougher.

The flow is the measure of the total deformation of the sample at the point of imminent failure. The stability at that point is also highest. Both the flow and stability are measured through the following procedure: The specimen is immersed in a water bath at 140° F (representing the hottest temperature the pavement would normally experience). The specimen is removed from the bath, the surface is dried as fast as possible while the sample is placed in a mold apparatus. The apparatus exerts a steadily increasing load until the sample fails. The stability and flow results are taken at that point.

Very low flow values would indicate a brittle mix, while high flow values represent a fluid plastic mix that tends to distort easily under load. The flow values from the CD samples varied from high of 15.7 (1/100 inches) to a low of 11.3 (1/100 inches). The highest value of 15.7 came from the 3.5% asphalt cement content that also has a lower stability. At 4.5% and 5.0 % the values were closer to 11 which is the median of the range specified by USDOT for flow (ie, 8 to 14). The flow values for the LPS samples were even better. They were all within the range of the specified values.

The specific gravity (Gmb) or bulk unit weight of a Marshall plug (sample) is a measure of weight per volume and is expressed in relation to water. A plug with a density of 2.5 is two and a half times as heavy as water. Water weighs 62.4 pcf, so a plug with a Gmb of 2.4 would have a density of (2.5 * 62.4) or 156pcf. The process to determine the Gmb is to weigh the plug, and to weigh it again under water. The amount of water the plug replaces is the volume of the plug, and the weight of the plug will be reduced by the amount of water displaced. Voids , VMA, and VFA are all computed from the Specific Gravity.

The VMA (voids in mineral aggregate) can be computed by subtracting the volume of the aggregate (using bulk SpGr) from the bulk volume of the plug. The values for both tests were well within the range specified by USDOT.

3.2.9 Changes in the Mix Designs

However, since the stability was not above the 1800lb minimum required for heavy traffic surfaces, the decision was made to substitute some of the larger size aggregates from the vitrified samples with regular aggregate. Beside the substitution of aggregates, no change was made to the original Colony Diner mix. The Liberty State Park mix was not only modified in terms of the vitrified material being substituted, the mix design was also readjusted. The newer mix design for LSP is shown in figure 5. The new results for both sites are listed in tables 13 and 14 and figures16 through 25.

3.2.10 Results after Changes

The use of 40% regular aggregate instead of the original 20% resulted in much better results. The stability values of the Colony Diner samples were greater than the 1800lbs required by USDOT for heavy traffic. The VMA was consistent with the previous results. It was well with the normally acceptable range required by USDOT for the nominal aggregate size of ¾". The percent air voids continued to meet USDOT requirements at the higher stability points which also coincided with the asphalt content of 5.5%. The flow fell exactly within the range of 8 to 14 required for heavy traffic pavements. That mix design was kept and the asphalt content of 5.0 was used for other tests.

The basic modifications in the LSP mix design and aggregate type greatly improved the stability of the mixes. The stability nearly doubled for each asphalt cement percentage. At the asphalt content of 5.5%, the average stability barely exceeded (by 25lbs) the 1800lbs minimum necessary for heavy traffic pavement as per USDOT. The other parameters like flow, air voids, and VMA were also within the within the USDOT specifications.

3.3 Durability of the Asphalt Mix

3.3.1 Purpose of the Tests

The freeze-thaw and wet-dry methods (ASTM D4867-88) were employed to determine the durability of the specimens. These tests are used to evaluate the ability of the asphalt concrete matrix to withstand harsh weather without accelerated aging beyond

the normal aging process. They measure the effect of moisture damage on asphalt concrete. The tensile strengths of moisture conditioned specimens are compared to the tensile strength of the control specimens.

The wet-dry and freeze-thaw tests (ASTM 4867-88) were conducted using the asphalt concrete mixture containing the vitrified aggregate having optimum asphalt contents. This method is used to test asphalt concrete mixtures in conjunction with mixture design. The control specimens were also tested with the optimum asphalt content.

3.3.2 Freeze-Thaw Procedure

A total of nine specimens were prepared for the purpose of this test and the wet-dry test. The nine specimens were divided into three subsets. Three specimens were used for moisture condition testing and three others for dry-conditioning. The specimens bulk and theoretical specific gravities as well as the air voids were determined. The three specimens that were to be dry-conditioned were stored at room temperature. The other three specimens were partially saturated to a value between 55% to 80% with distilled water using a vacuum chamber. Any specimen that was above 80% saturation was discarded. The three specimens needed for the freeze-thaw procedure were wrapped tightly in two layers of plastic using masking tape. They were then inserted in leak-free plastic bags with distilled water. The samples were subsequently sealed, marked and placed in a freezer at -18°C. After 15 hours, the specimens were taken out of the freezer and placed it in a bath at 60°C for 24 hours. Subsequent to the freeze-thaw procedure,

the following parameters were determined: Bulk specific gravity, height (ASTM D-3549), volume (ASTM D-2726), and swell. Swell was calculated with the use of the initial specimen volume.

The moisture conditioned specimens along with the dry conditioned specimens were placed in the 25°C water bath for 30 minutes after which the indirect tensile strength test was performed to determine the maximum tensile load. The formula used to calculate the tensile strength is shown below:

$$St = 2*P/(\prod*t*D)$$

where:

St = tensile strength, psi

P = maximum load, lbs

t = specimen height, in

D = specimen diameter, in

The tensile strength ratio is calculated as shown below:

$$TSR = (Stm/Std)*100$$

where:

TSR = tensile strength ratio, %

Stm = average tensile strength of the moisture conditioned subset, psi

Std = average tensile strength of the dry conditioned subset, psi

3.3.3 Wet-Dry Procedure

The remaining three specimens out of the previously prepared nine samples were used for the freeze-thaw procedure. The same procedures were followed for compaction, and

testing as it is in the previous sections. The only difference between this procedure and the freeze-thaw test is that the specimens are placed in a water bath at 60°C for 24 hours instead of the freezer. After the bulk and theoretical specific gravity were determined, the same procedure followed in the previous section was used to find the tensile strength. The swell, tensile strength, and tensile strength ratio (TSR) were also determined in the same way as in the freeze-thaw section.

Table 16 Tensile Strength Ratio (Freeze-thaw)

Samples	Tensile Strength Ratio (%)	Swell (%)
Colony Diner	98 *	1.5 *
Liberty State Park	92 *	2.2 *

Table 17 Tensile Strength Ratio (Wet-dry)

Samples	Tensile Strength Ratio (%)	Swell (%)
Colony Diner	100 *	1.5 *
Liberty State Park	96 *	2.2 *

* *Each number represents the average of three values.*

3.3.4 Analysis of Results

The tensile strength of all the samples tested remained very high after both the wet/dry and the freeze/thaw tests. The lowest value for the tensile strength ratio was 92%, incurred by the average of three LSP samples for the freeze/thaw test; the highest was 100%. The swell was also negligible in all the cases. The highest swell value was only 2.5%. It is worth noting that in these tests again the CD samples performed better that than the LSP samples. The results show that the mix containing the vitrified aggregate

would not be any more affected by weathering than a containing only regular aggregate, hence the asphalt mix containing the vitrified aggregate can be very durable.

3.4 Permeability

Permeability is the ability of a medium to transmit fluids because of its porosity. That characteristic is undesirable in an asphalt mix because it increases the likeliness of deterioration of the asphalt pavement. In asphalt mixes, hydraulic conductivity is governed by the size and shape of the voids, the interconnection between the voids, and the physical properties of the penetrating fluid. It is necessary for a good asphalt concrete mix to have a minimum of 3% air voids. Problems arise not from the fact that the asphalt mix has voids but the amount of tubes in the compacted asphalt pavement. The term "tube" refers to the continuous connection between the air voids. Hydraulic conductivity is directly proportional not only to the amount of interconnected voids (tube) but also to the access of these tubes to the surface of the pavement.

The are currently two predominant methods used to measure hydraulic conductivity in a laboratory setting: Constant head and falling head. The falling head method was used to determine the hydraulic conductivity of the asphalt concrete samples in this research.

3.4.1 Effects of Permeability in Asphalt Pavement

Even more than concrete, asphalt pavement is generally very open to weathering. the durability of the asphalt pavement is greatly reduced by the penetration elements like air and water. When water freezes in the tubes, its volume increases by a maximum of 9%.

CHAPTER 4

CONCLUSION

The incorporation of ex-situ cold top vitrified aggregate from chromium contaminated soil provides an effective means for treatment of the contaminated soils. It further provides valuable aggregates that would otherwise have to be mined. In the foreseeable future, there will always be a need for aggregate use in asphalt pavement, concrete, and others. As any other natural resource, once rock is disturbed from its natural location, the process cannot be reversed, hence humanity's duty to conserve rock in its natural position and state as much as possible. On the other hand, the soil that has been contaminated, by chromium for example, which is the case in the Hudson County, NJ, must be remediated.

The pilot scale evaluation of vitrification of chromium contaminated soils done by Meegoda et al (1995, 1996) clearly shows the effectiveness of the vitrification procedure to not only treat the chromium contaminated soil and but also to produce an aggregate that has all the required properties of hot mix asphalt pavement. This bench scale research has further confirmed the properties of the vitrified material. Additionally, it has shown the performance of the vitrified material in the asphalt matrix. The tests used in this research are standard in the hot mix asphalt industry and they are generally performed before the use of any new source of aggregate or mix design to accurately predict the eventual performance of the asphalt mix (containing the new aggregate) in the field.

The Marshall test results clearly showed that the incorporation of as much as 58.8% of vitrified aggregate in the asphalt mix produced an asphalt concrete that meets all the USDOT specifications for asphalt pavement. The original inclusion of 80% of vitrified aggregate in the asphalt mix produced results that would be satisfactory for low and medium traffic only. However, with the inclusion of only 58.8% of the vitrified material in the asphalt mix produced excellent results.

It can be concluded that reuse of cold top ex-situ vitrification of chromium contaminated soil as asphalt pavement aggregate is a very feasible technology that would permanently treat the contaminated material and also provide a good aggregate. It is however necessary to evaluate different chromium contaminated sites on an individual basis. The vitrified materials from the two different sites used in this research performed different in some of the tests. The more glassy material from LSP was not as effective as the CD material that looked and felt like regular rock. The financial aspects of this technology should also be evaluated before any large field test is done.

APPENDIX A

FIGURES OF TESTS RESULTS

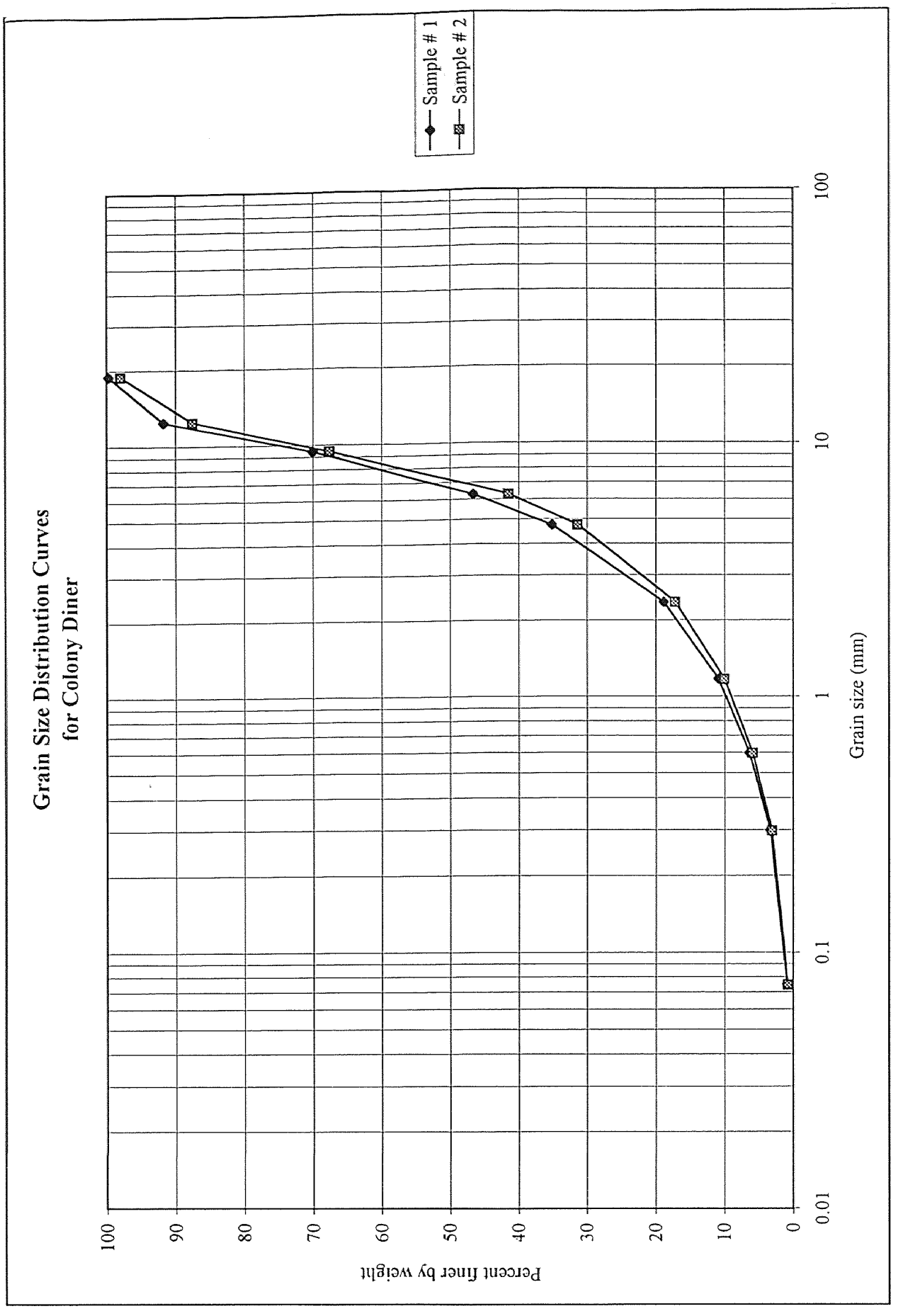

Figure 1 Grain Size Distribution for Colony Diner Samples 1 and 2

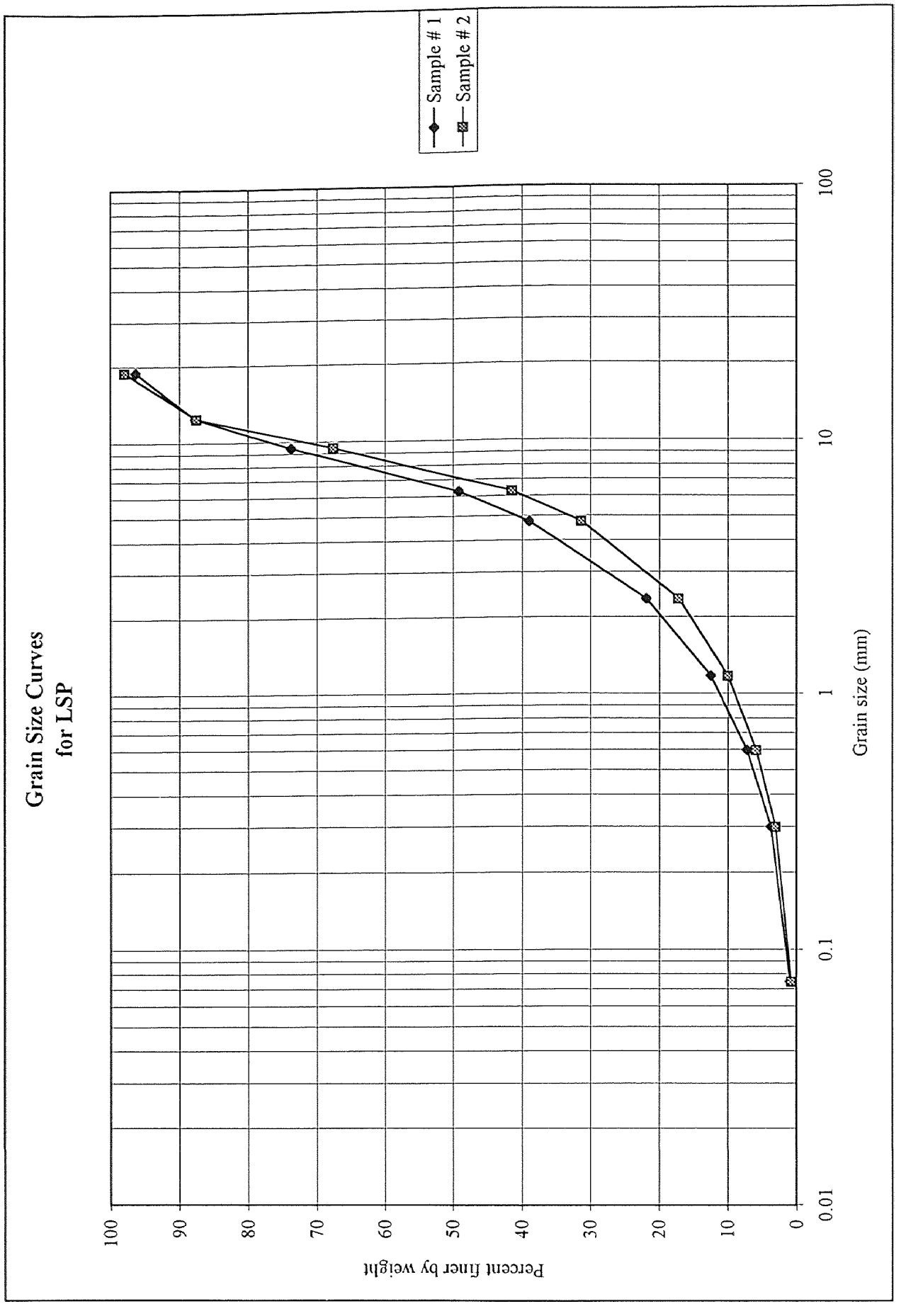

Figure 2 Grain Size distribution for LSP Samples 1 and 2

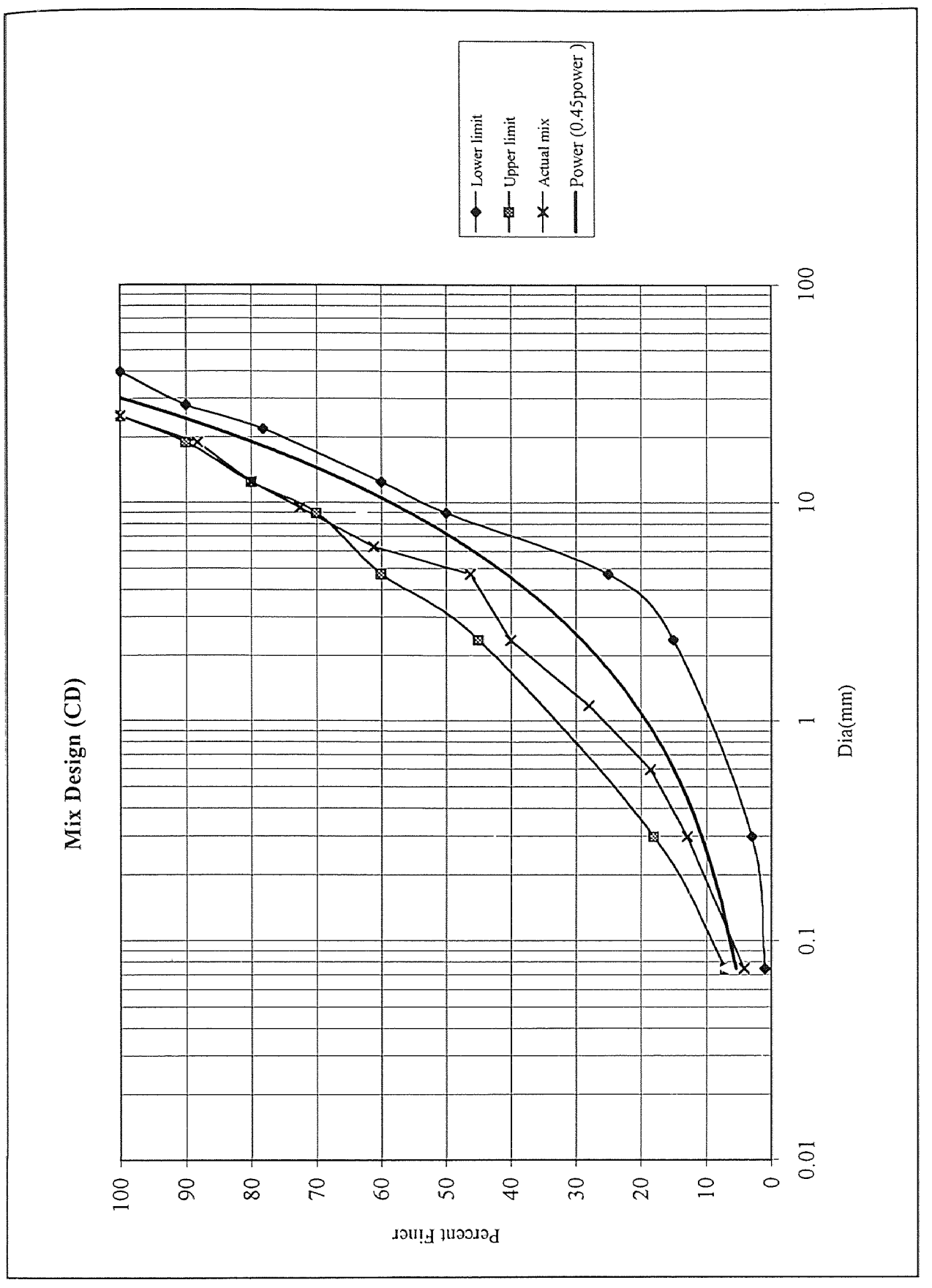

Figure 3 Mix Design for CD

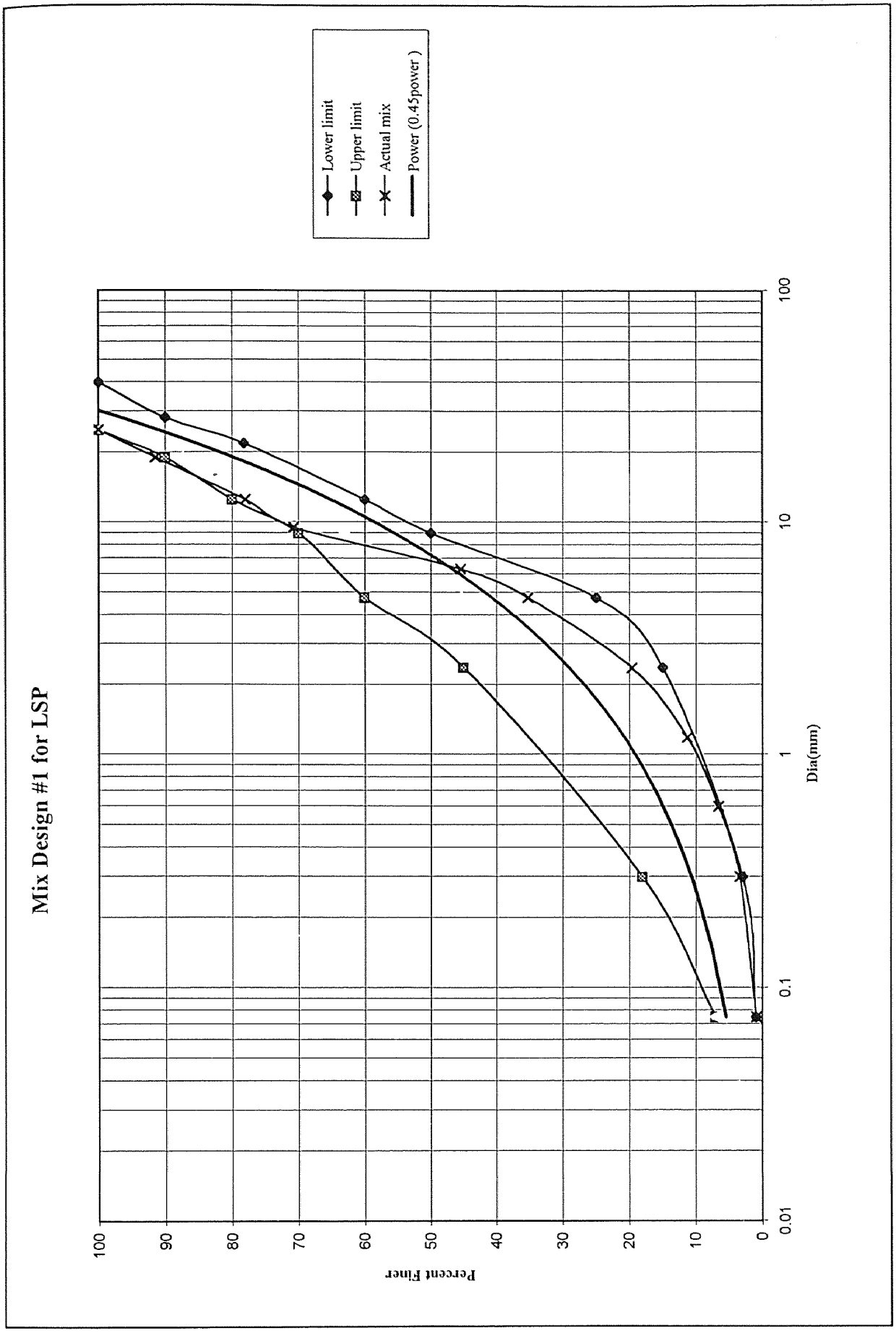

Figure 4 Mix Design for LSP #1

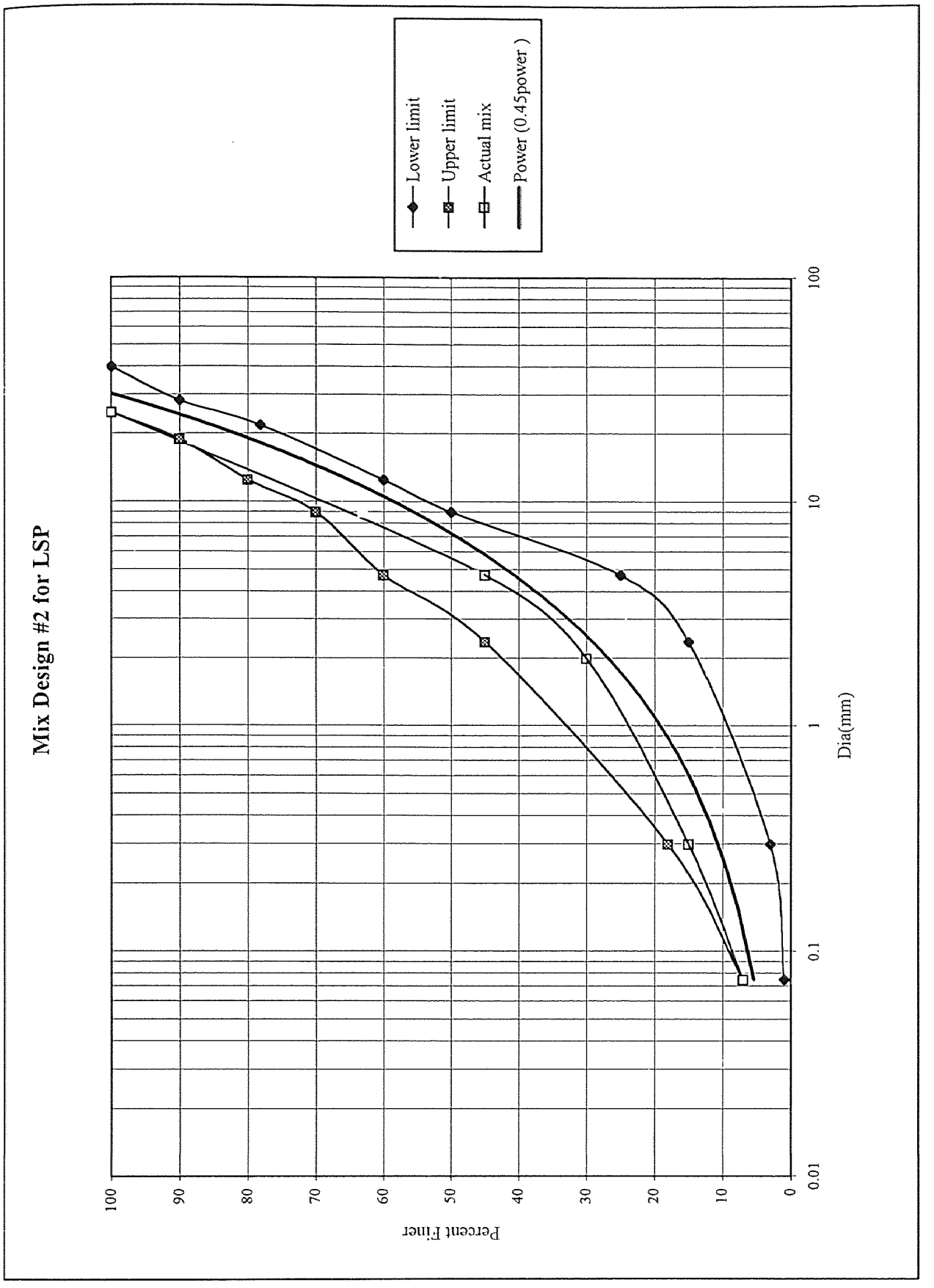

Figure 5 Mix Design for LSP #2

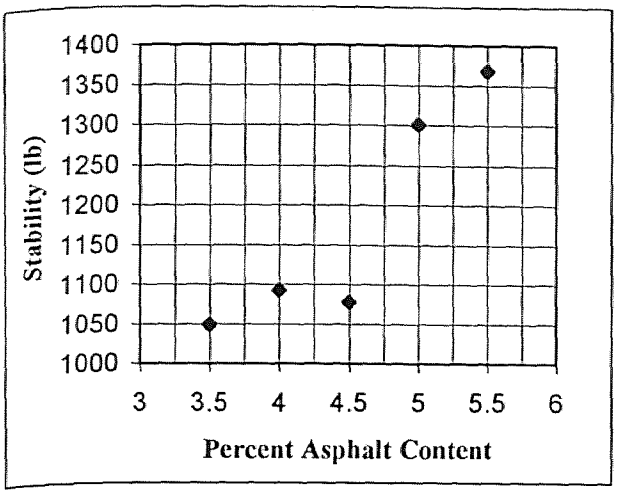

Figure 6 Asphalt Content Vs Stability

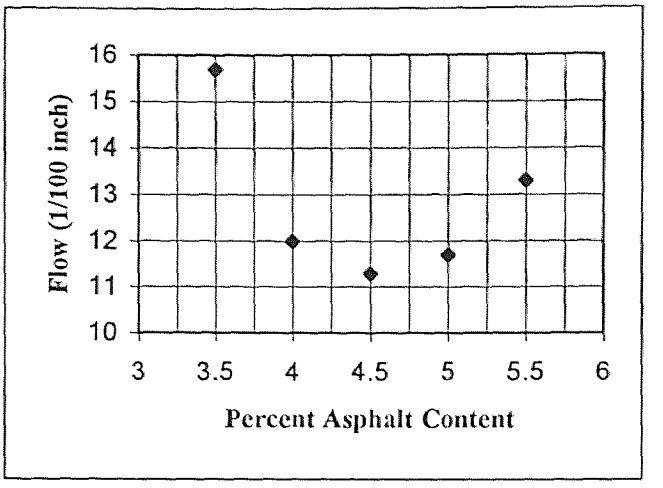

Figure 7 Asphalt Content Vs Flow

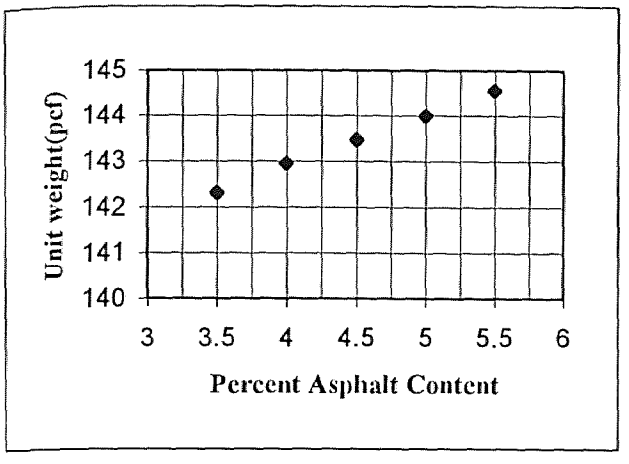

Figure 8 Asphalt Content Vs Unit Weight

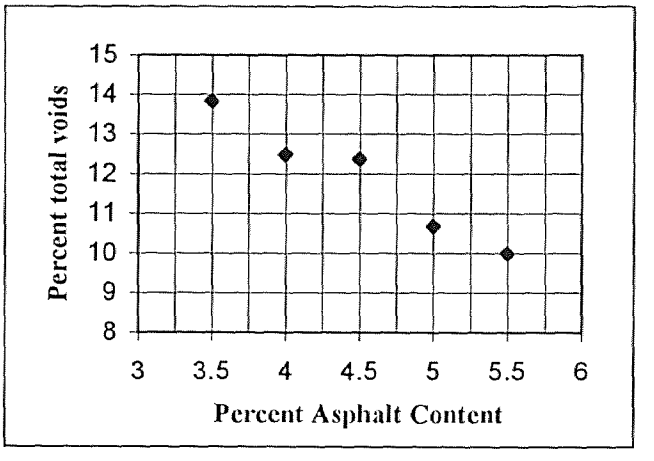

Figure 9 Asphalt Content Vs Air Voids

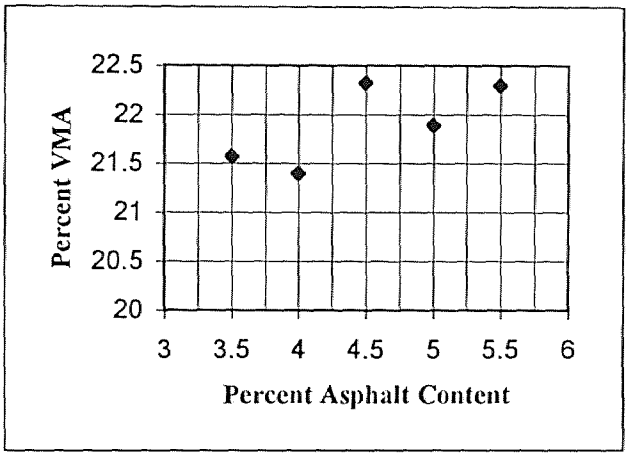

Figure 10 Asphalt Content Vs VMA

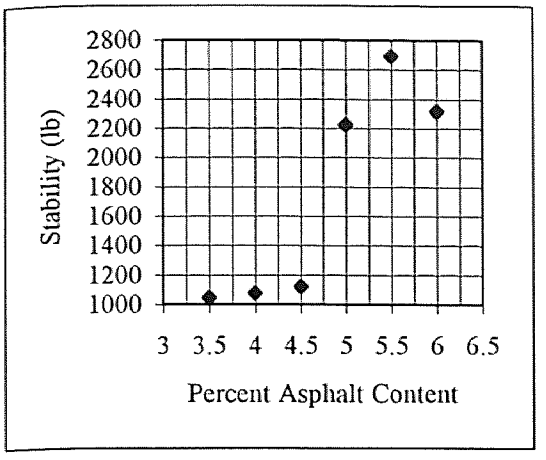

Figure 11 Asphalt Content Vs Stability

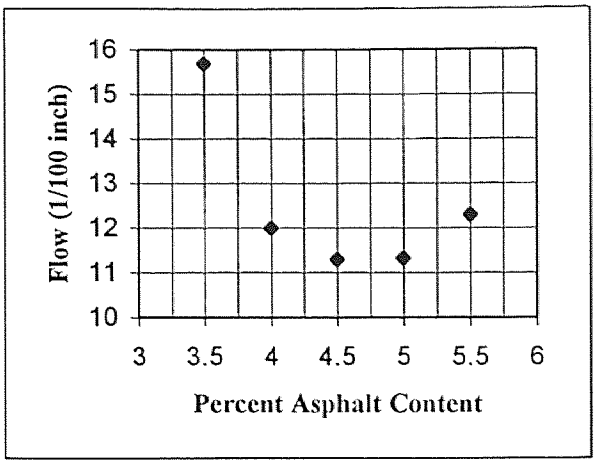

Figure 12 Asphalt Content Vs Flow

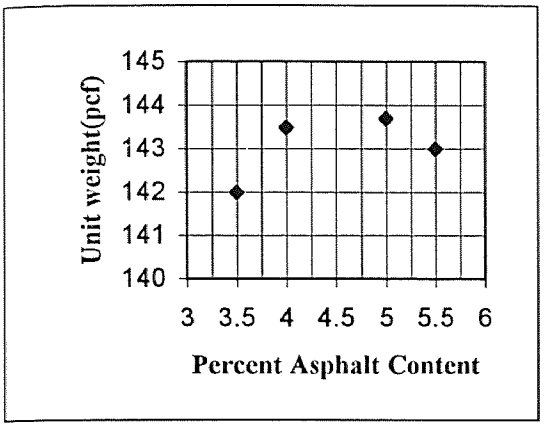

Figure 13 Asphalt Content Vs Unit Weight

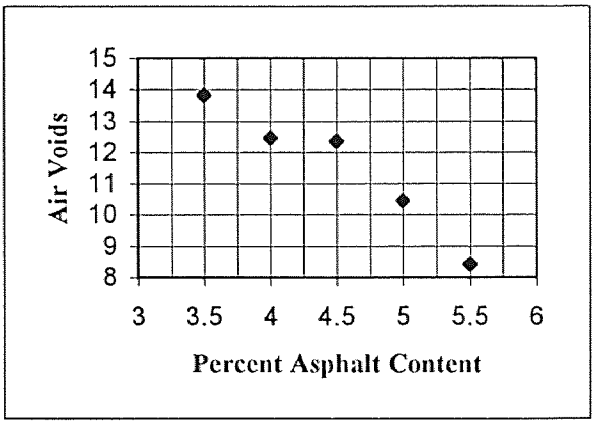

Figure 14 Asphalt Content Vs Total Voi

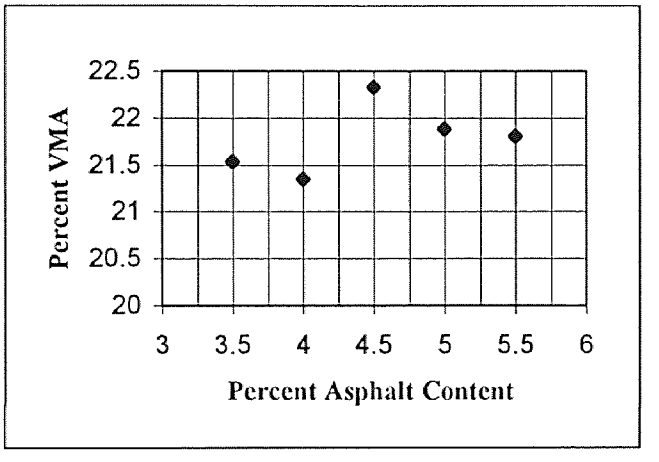

Figure 15 Asphalt Content Vs VMA

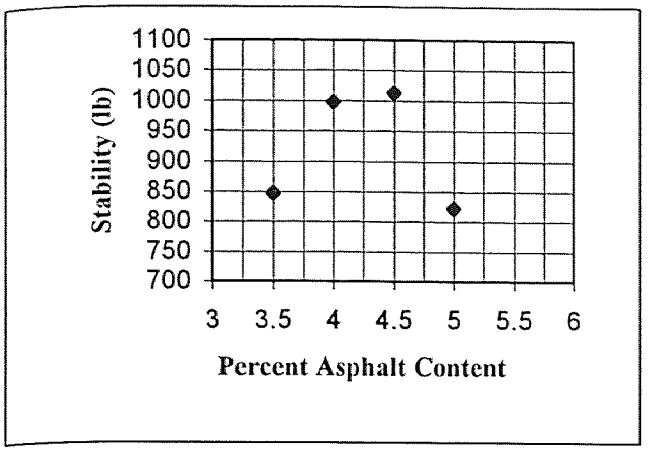

Figure 16 Asphalt Content Vs Stability

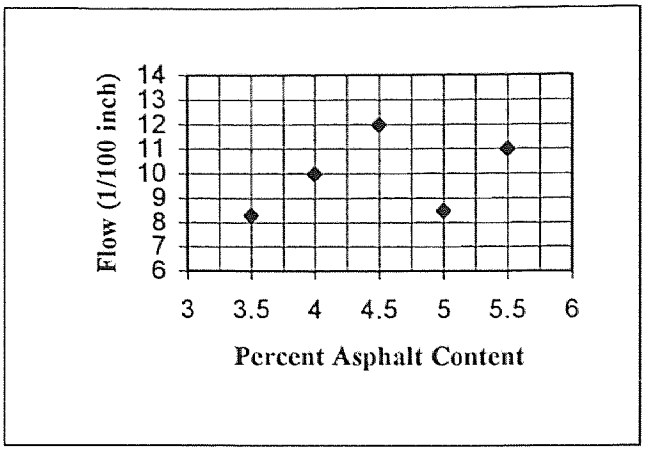

Figure 17 Asphalt Content Vs Flow

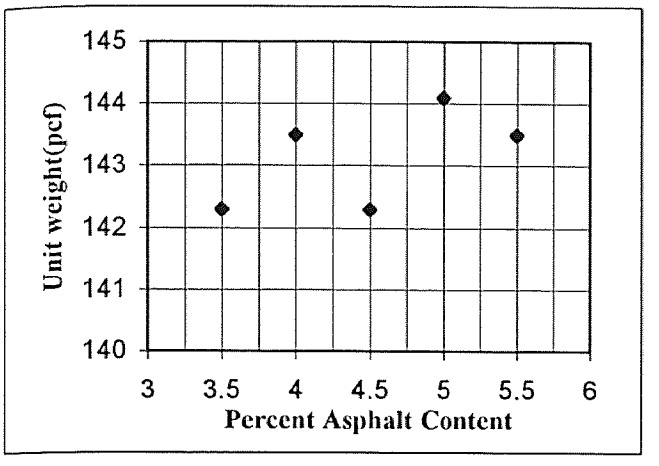

Figure 18 Asphalt Content Vs UnitWeight

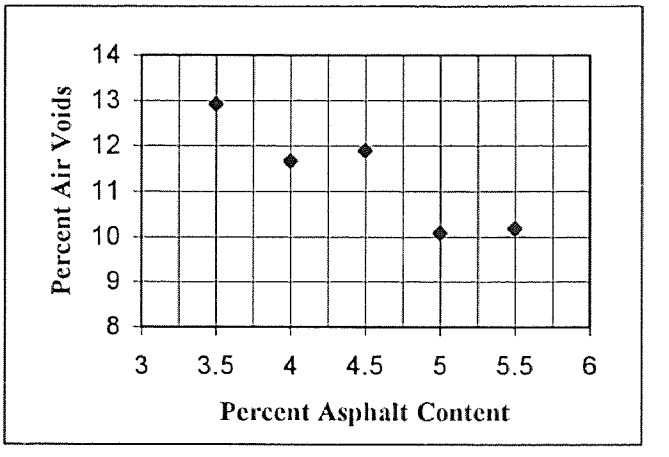

Figure 19 Asphalt Content Vs Air Voids

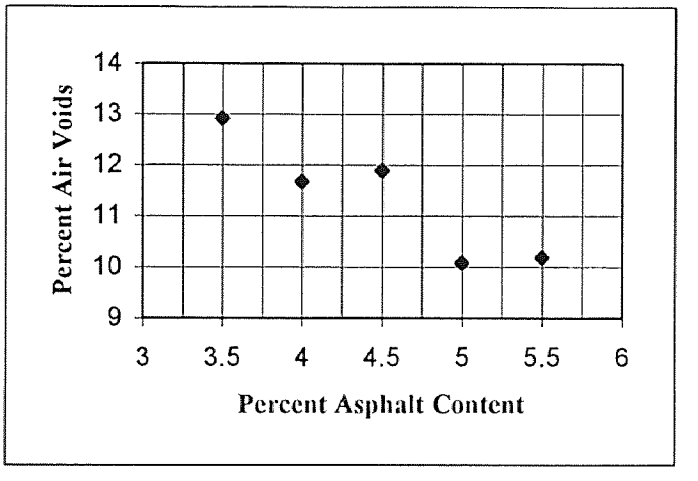

Figure 20 Asphalt Content Vs VMA

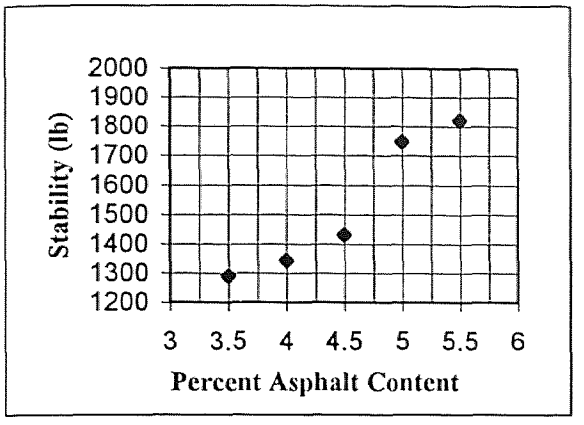

Figure 21 Asphalt Content Vs Stability

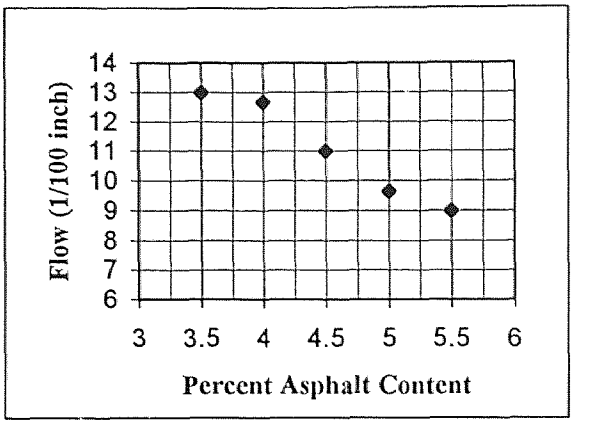

Figure 22 Asphalt Content Vs Flow

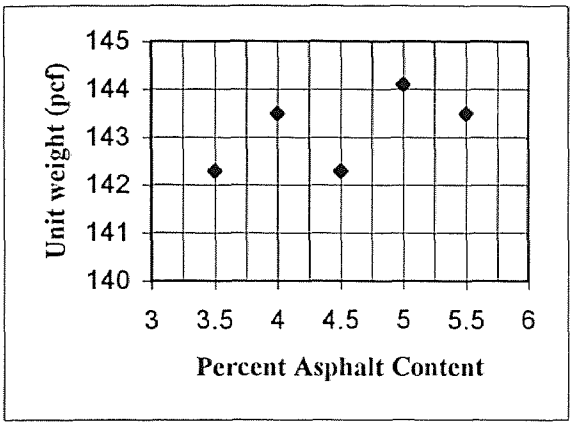

Figure 23 Asphalt Content Vs Unit Weight

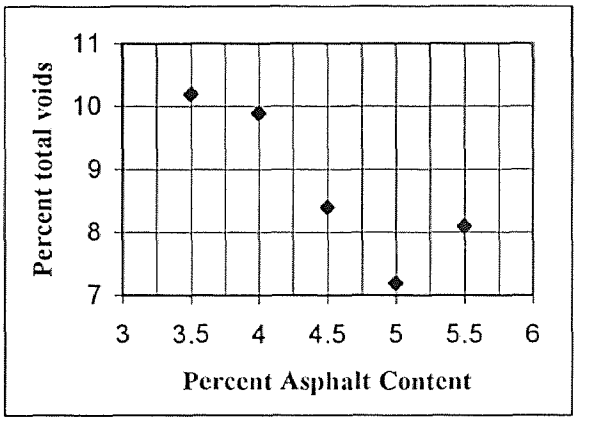

Figure 24 Asphalt Content Vs Air Voids

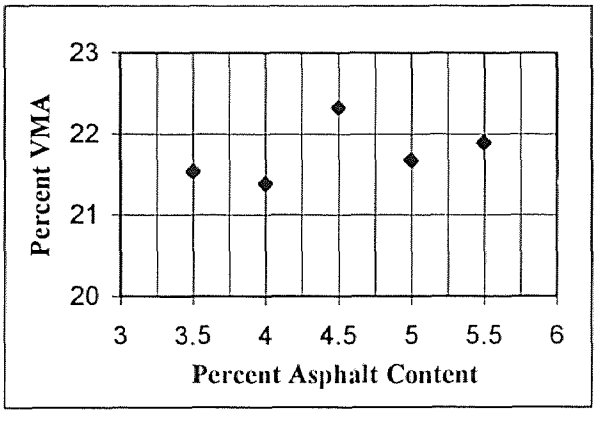

Figure 25 Asphalt Content Vs VMA

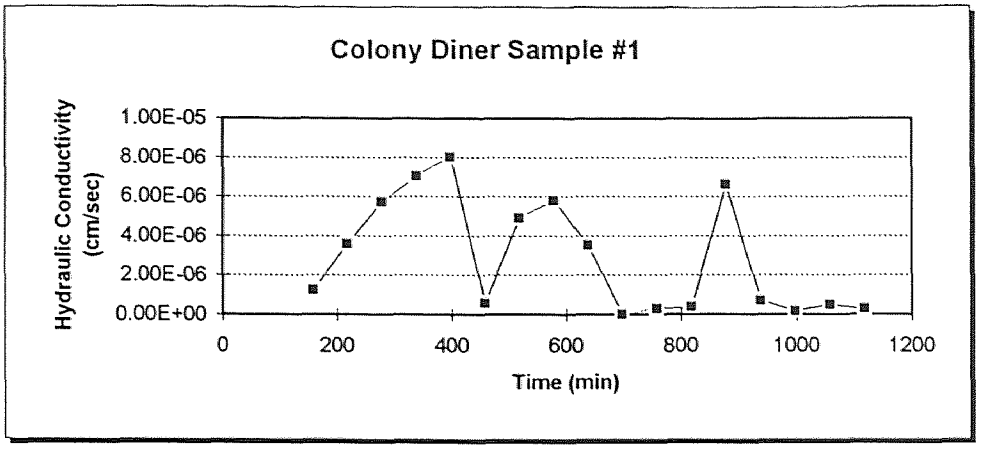

Figure 26

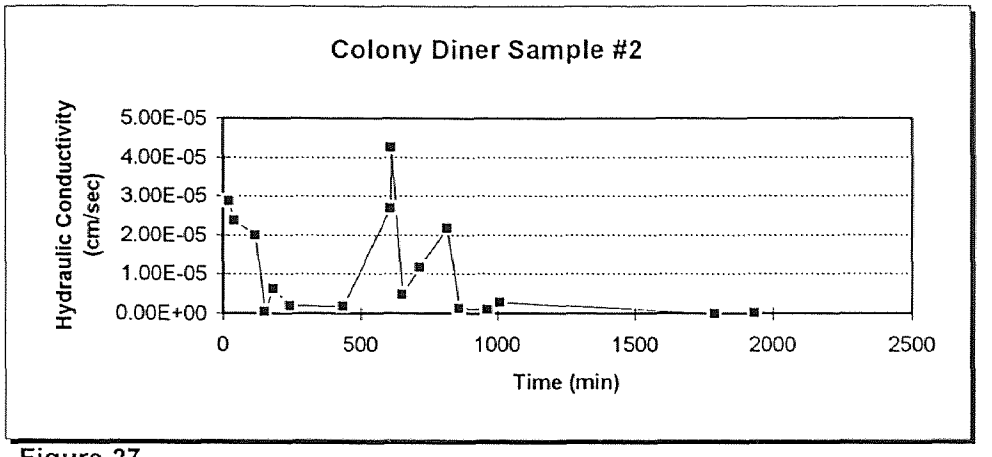

Figure 27

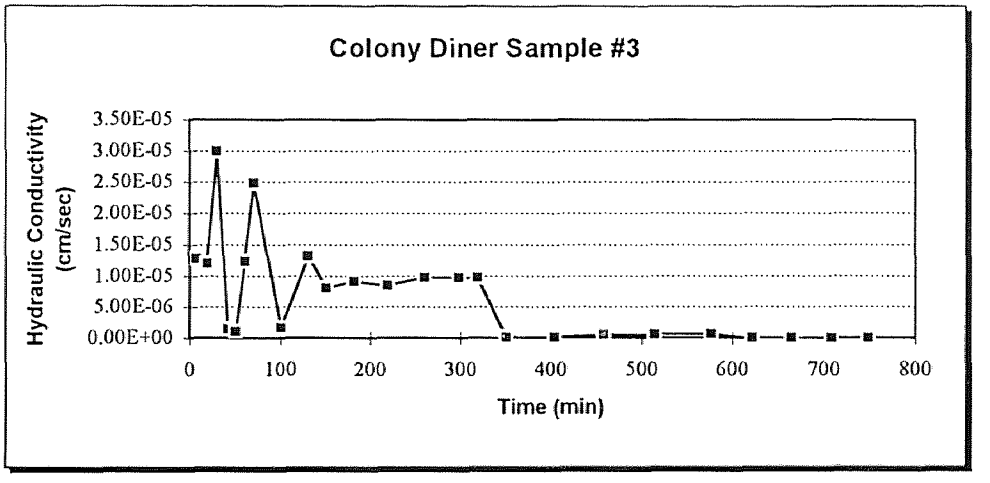

Figure 28

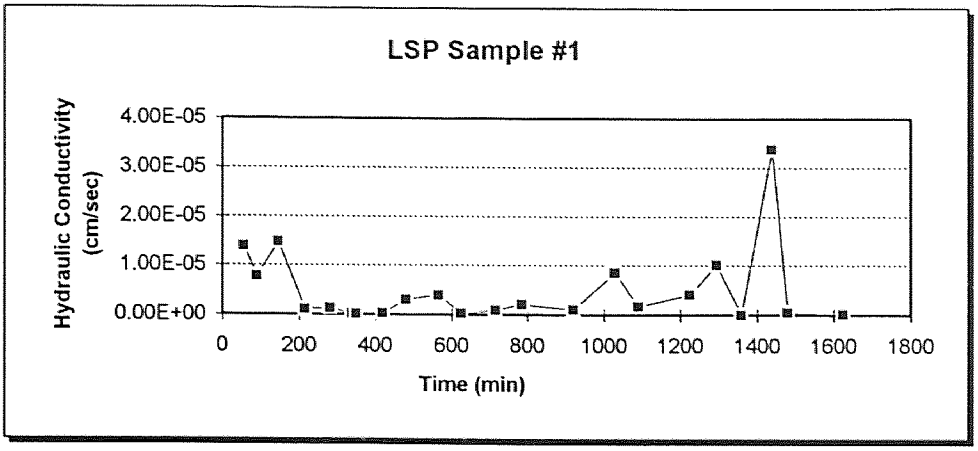

Figure 29

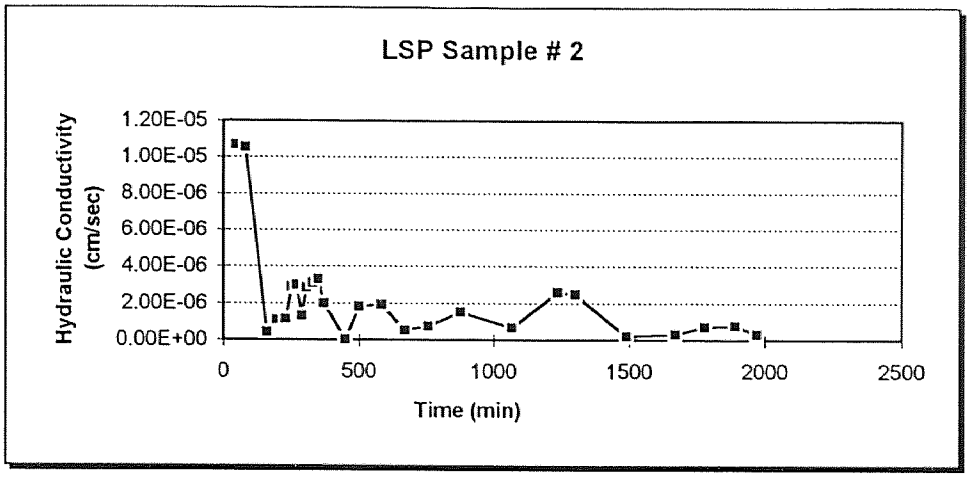

Figure 30

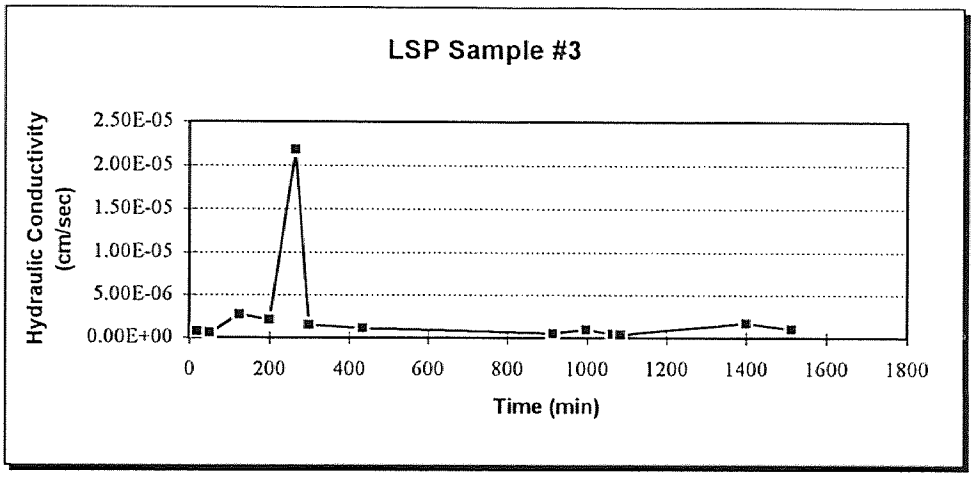

Figure 31

APPENDIX B

LIST OF TABLES

Table 1 Los Angeles Abrasion Test (Colony Diner)

Grading	Original Weight (g)	Retained after 100 Rotations		Retained after 500 Rotations		Percentage Loss	Uniformity
		Weight (g)	Percentage	Weight (g)	Percentage		
C	5000	4526	91	3204	64.1	35.9	0.26
D	5000	4586	92	3464	69.3	30.7	0.27

Table 2 Los Angeles Abrasion Test (Liberty State Park)

Grading	Original Weight (g)	Retained after 100 Rotations		Retained after 500 Rotations		Percentage Loss	Uniformity
		Weight (g)	Percentage	Weight (g)	Percentage		
C	5000	4430	88.6	3318	66.36	33.64	0.33
D	5000	4472	89.4	3447	68.94	31.06	0.34

Table 3 Sieve Analysis #1 (Liberty State Park)

Sieve		Mass Retained (g)	Percentage Retained	Percentage Passing
Number	Size (mm)			
3\4	19.00	57.0	6.67	93.33
1\4	6.30	223.3	32.76	67.24
#4	4.75	58.3	39.57	61.43
#10	2.00	122.1	53.84	46.16
#40	0.425	151.7	71.51	28.49
#70	0.212	63.1	78.94	21.06
#200	0.075	85.9	88.98	11.02
Pan	0.000	94.4	100.01	0
Total		855.8		

Table 4 Sieve Analysis #1 (Colony Diner)

Sieve		Mass Retained (g)	Percentage Retained	Percentage Passing
Number	Size (mm)			
3\4	19.00	10.5	0.27	99.73
1\2	12.5	317.9	8.22	91.78
3\8	9.5	1158.1	29.96	70.04
1\4	6.30	2061.4	53.32	46.68
#4	4.75	2507.5	64.86	35.14
#8	2.36	3137.4	81.15	18.85
#16	1.18	3446.8	89.15	10.85
#30	0.60	3622.1	93.69	6.31
#50	0.30	3737.9	96.68	3.32
#200	0.075	3833.1	99.15	0.85
Pan	0.000	3866.1	100	0.00
Total		3866.1		

Table 5 Sieve Analysis #2 (Liberty State Park)

Sieve		Mass Retained (g)	Percentage Retained	Percentage Passing
Number	Size (mm)			
3\4	19.00	60.1	2.05	97.95
1\2	12.5	365.5	12.47	87.53
3\8	9.5	951.7	32.46	67.54
1\4	6.30	1715.5	58.51	41.49
#4	4.75	2011.9	68.61	31.39
#8	2.36	2428.7	82.83	17.17
#16	1.18	2638.3	89.98	10.02
#30	0.60	2760.1	94.13	5.87
#50	0.30	2842.3	96.93	3.07
#200	0.075	2910.5	99.26	0.74
Pan	0.000	2932.2	100.00	0.00
Total		2932.2		

Table 6 Sieve Analysis #3 (Liberty State Park)

Sieve		Mass Retained (g)	Percentage Retained	Percentage Passing
Number	Size (mm)			
3\4	19.00	84.4	3.67	96.33
1\2	12.5	283.0	12.31	87.69
3\8	9.5	603.6	26.25	73.75
1\4	6.30	1168.5	50.82	49.18
#4	4.75	1403.3	61.03	38.97
#8	2.36	1796.9	78.15	21.85
#16	1.18	2012.5	87.53	12.47
#30	0.60	2133.3	92.78	7.22
#50	0.30	2214.0	96.29	3.71
#200	0.075	2277.6	99.06	0.94
Pan	0.000	2299.3	100.00	0.00
Total		2299.3		

Table 7 Sieve Analysis #2 (Colony Diner)

Sieve		Mass Retained (g)	Percentage Retained	Percentage Passing
Number	Size (mm)			
3\4	19.00	60.1	2.05	97.95
1\2	12.5	365.5	12.47	87.53
3\8	9.5	951.7	32.46	67.54
1\4	6.30	1715.5	58.51	41.49
#4	4.75	2011.9	68.61	31.39
#8	2.36	2428.7	82.83	17.17
#16	1.18	2638.3	89.98	10.02
#30	0.60	2760.1	94.13	5.87
#50	0.30	2842.3	96.93	3.07
#200	0.075	2910.5	99.26	0.74
Pan	0.000	2932.2	100.00	0.00
Total		2932.2		

Table 8 Friable and Clay Lumps (CD)

Type of Aggregate	Test Sample Weight (g)	Friable & Clay Lump (%)
Fine Aggregates	150	0.78
Coarse Aggregates	1200	0.06

Table 9 Friable and Clay Lumps (LS P)

Type of Aggregates	Test Sample Weight (g)	Friable & Clay Lump (%)
Fine Aggregates	150	0.81
Coarse Aggregates	1200	0.07

Table 10 Sodium Sulfate Test for Fine Aggregate (Colony Diner)

Sieve Size		Original Weight of Sample(g)	Percentage Loss (%)
Passing	Retained		
#4	#8	100	2.10
3/8	#4	150	1.80

Table 11 Sodium Sulfate Test for Coarse Aggregate (Liberty State Park)

Sieve Size		Original Weight of Sample(g)	Percentage Loss (%)
Passing	Retained		
¾"	3/8"	800	3.10

Table 12 Marshall Test Results (Colony Diner)

AC %	Dry Wt. (gr)	Volume cc	Flow 1/100 in	Stability (lb)	Tot. V. %	VMA %	Bulk SG (pcf)
3.5	1228	536	16	1425			
3.5	1198	531	17	1535			
3.5	1251	545	15	1450			
Avg	**1226**	**537**	**15**	**1470**	10.2	21.52	142.32
4.0	1249	541	15	1550			
4.0	1201	523	16	1650			
4.0	1230	542	14	1600			
Avg	**1227**	**536**	**15**	**1600**	8.9	21.49	142.96
4.5	1215	525	11	1800			
4.5	1253	545	13	1950			
4.5	1236	541	11	1975			
Avg	**1235**	**537**	**12**	**1925**	8.8	21.64	143.47
5.0	1246	546	11	2132			
5.0	1289	563	11	2100			
5.0	1259	535	12	2450			
Avg	**1265**	**548**	**11**	**2227**	7.0	22.00	144.03
5.5	1226	532	12	3025			
5.5	1271	550	12	2150			
5.5	1312	562	13	2900			
Avg	**1270**	**548**	**12**	**2691**	6.5	21.81	144.55

Table 13 Marshall Test Results (LSP 1)

AC %	Dry Wt. (gr)	Volume (cc)	Flow 1/100 in	Stability (lb)	Air Voids %	VMA %	Bulk Unit Wt. (pcf)
3.5	1216	526	8.0	795			
3.5	1209	524	9.0	845			
3.5	1222	536	8.0	903			
Avg.	**1215**	**529**	**8.3**	**848**	**8.3**	**20.74**	**143.5**
4.0	1199	519	10.0	863			
4.0	1225	529	9.0	993			
4.0	1241	536	11.0	1143			
Avg.	**1221**	**528**	**10.0**	**999**	**7.0**	**20.67**	**144.5**
4.5	1223	534	11.5	1013			
4.5	1222	529	12.0	1175			
4.5	1223	539	12.0	853			
Avg.	**1222**	**534**	**12.0**	**1014**	**7.38**	**21.91**	**142.9**
5.0	1228	541	7.0	695			
5.0	1224	532	10.0	1061			
5.0	1226	536	9.0	715			
Avg.	**1226**	**536.5**	**8.5**	**823**	**6.7**	**22.31**	**142.9**
5.5	1238	540	11.0	509			
5.5	1217	529	12.0	662			
5.5	1227	553	10.0	561			
Avg.	**1227**	**541**	**11.0**	**577**	**6.9**	**22.47**	**141.6**

Table 14 Marshall Test Results (Colony Diner)

AC %	Dry Wt. (gr)	Volume cc	Flow 1/100 in	Stability lb	Tot. V. %	VMA %	Bulk SG pcf
3.5	1228	536	16	1425			
3.5	1198	531	17	1535			
3.5	1251	545	15	1450			
Avg	**1226**	**537**	**16**	**1470**	10.2	21.52	142.32
4.0	1249	541	15	1550			
4.0	1201	523	16	1650			
4.0	1230	542	14	1600			
Avg	**1227**	**535**	**15**	**1600**	8.9	21.49	142.96
4.5	1215	525	11	1800			
4.5	1253	545	13	1950			
4.5	1236	541	11	1975			
Avg	**1234**	**537**	**12**	**1908**	8.8	21.64	143.47
5.0	1246	546	11	2132			
5.0	1289	563	11	2100			
5.0	1259	535	12	2450			
Avg	**1265**	**548**	**11**	**2227**	7.0	22.00	144.03
5.5	1226	532	12	3025			
5.5	1271	550	12	2150			
5.5	1312	562	13	2900			
Avg	**1270**	**548**	**12**	**2691**	6.5	21.81	144.55

Table 15 Marshall Test Results (LSP 2)

AC %	Dry Wt. (gr)	Volume (cc)	Flow 1/100 in	Stability (lb)	Air Voids. %	VMA %	Bulk Unit Wt. (pcf)
3.5	1223	540	13	1330			
3.5	1257	554	12	1260			
3.5	1282	559	14	1310			
Avg.	**1254**	**551**	**13**	**1333**	**8.7**	**21.54**	**142.0**
4.0	1221	537	13	1350			
4.0	1279	553	12	1310			
4.0	1262	546	13	1375			
Avg.	**1235**	**545**	**12.7**	**1345**	**7.3**	**21.39**	**141.4**
4.5	1220	536	11	1500			
4.5	1257	554	12	1410			
4.5	1242	537	10	1390			
Avg.	**1240**	**542**	**11**	**1433**	**7.4**	**22.33**	**142.8**
5.0	1244	533	10	1720			
5.0	1220	526	9	1790			
5.0	1301	577	11	1800			
Avg.	**1255**	**542**	**10**	**1770**	**5.6**	**21.68**	**143.7**
5.5	1282	548	10	1810			
5.5	1272	552	9	1820			
5.5	1244	547	8	1840			
Avg.	**1243**	**549**	**9**	**1830**	**5.4**	**21.81**	**141.3**

Table 16 Tensile Strength Ratio (Freeze-thaw)

Samples	Tensile Strength Ratio (%)	Swell (%)
Colony Diner	98 *	1.5 *
Liberty State Park	92 *	2.2 *

Table 17 Tensile Strength Ratio (Wet-dry)

Samples	Tensile Strength Ratio (%)	Swell (%)
Colony Diner	100 *	1.5 *
Liberty State Park	96 *	2.2 *

* *Each number represents the average of three values.*

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